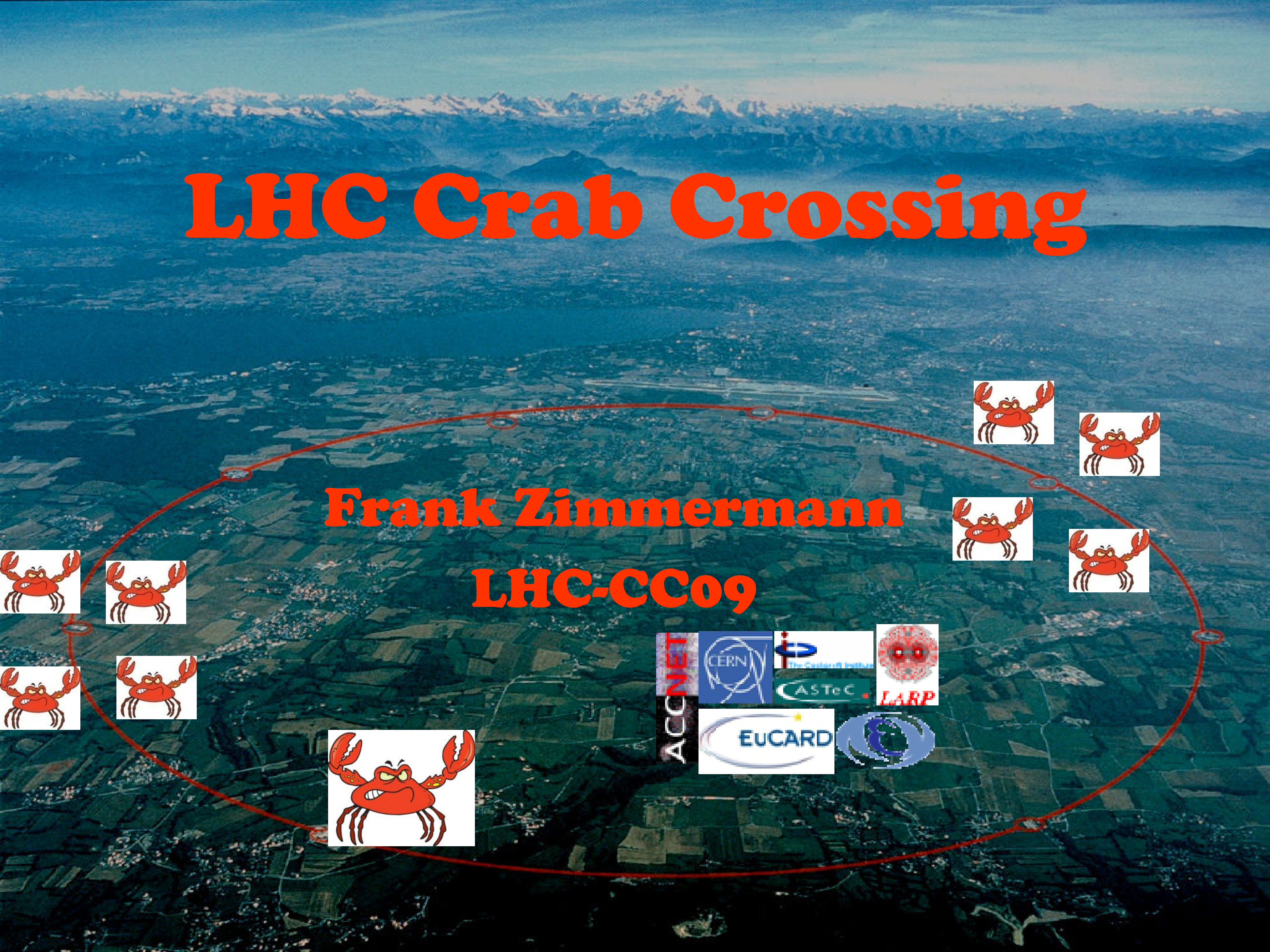
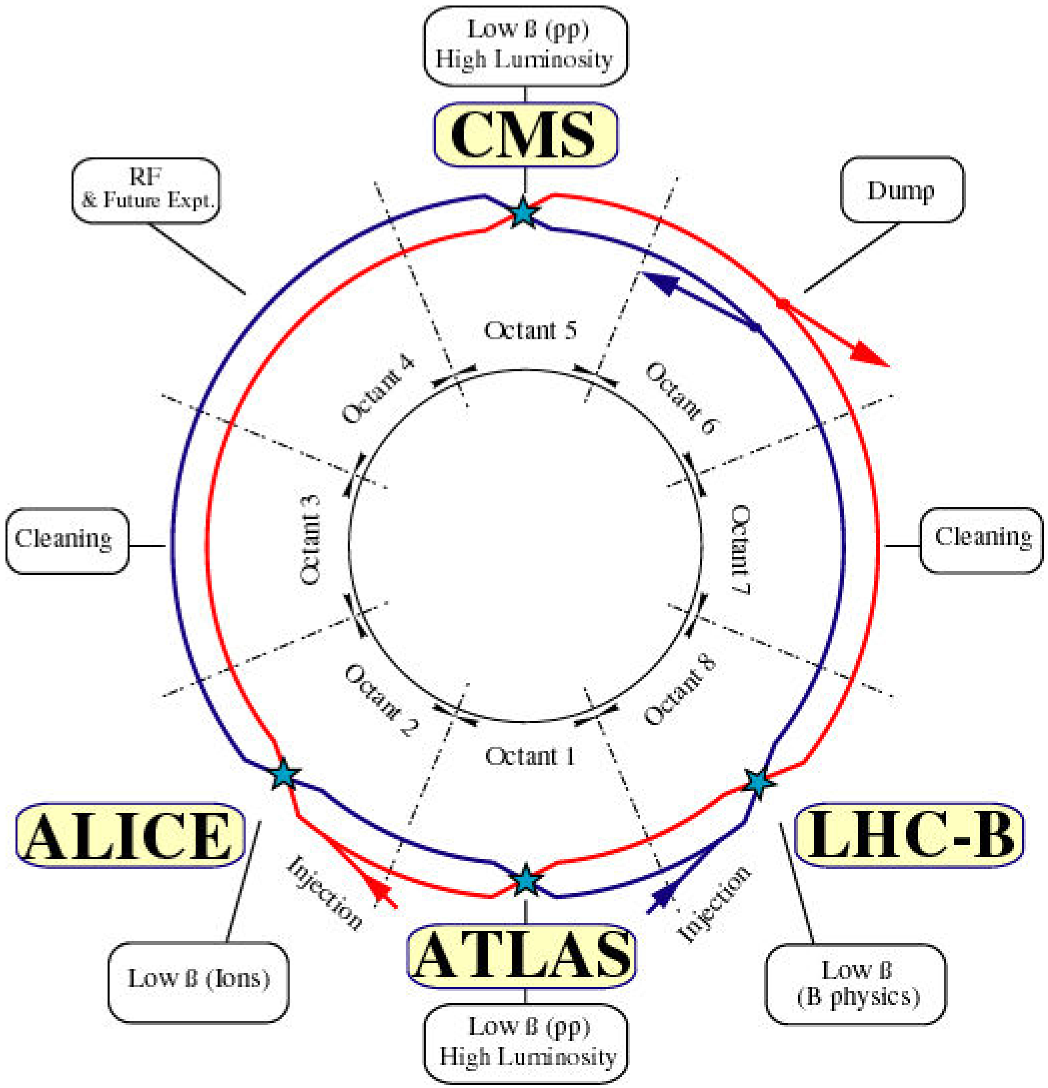
LHC Crab Crossing



Frank Zimmermann

LHC-CC09

Large Hadron Collider (LHC)



proton-proton and ion-ion collider

next energy-frontier discovery machine

c.m. energy 14 TeV (7x Tevatron)

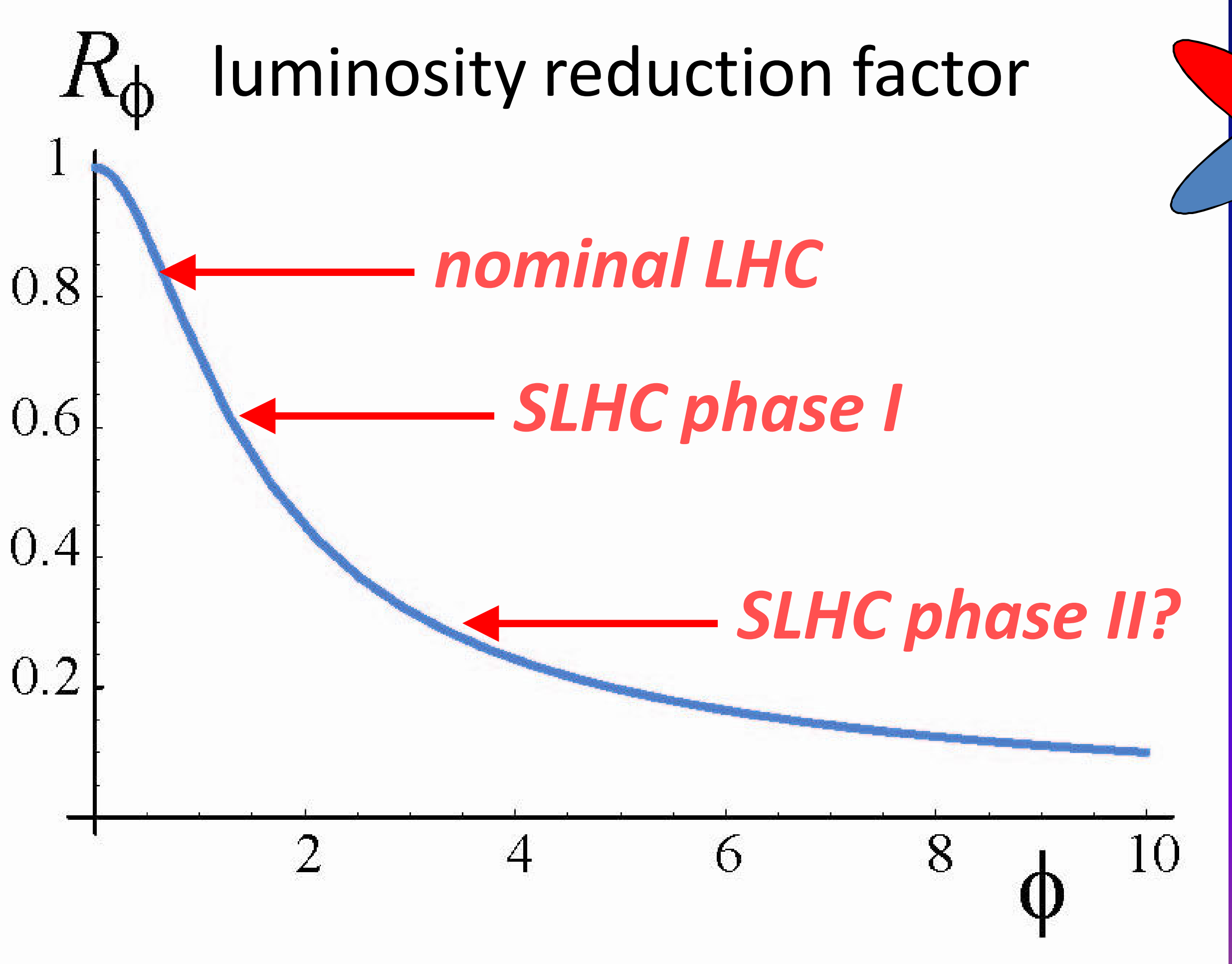
design pp luminosity 10^{34} $cm^{-2}s^{-1}$ (~30x Tevatron)

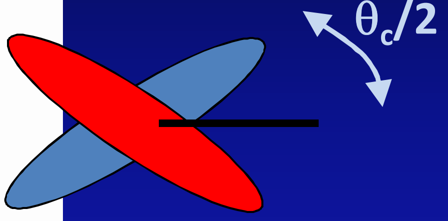
LHC baseline was pushed in competition with SSC (†1993)

crossing angle

$$R_\phi = \frac{1}{\sqrt{1+\phi^2}}; \quad \phi \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

"Piwinski angle"

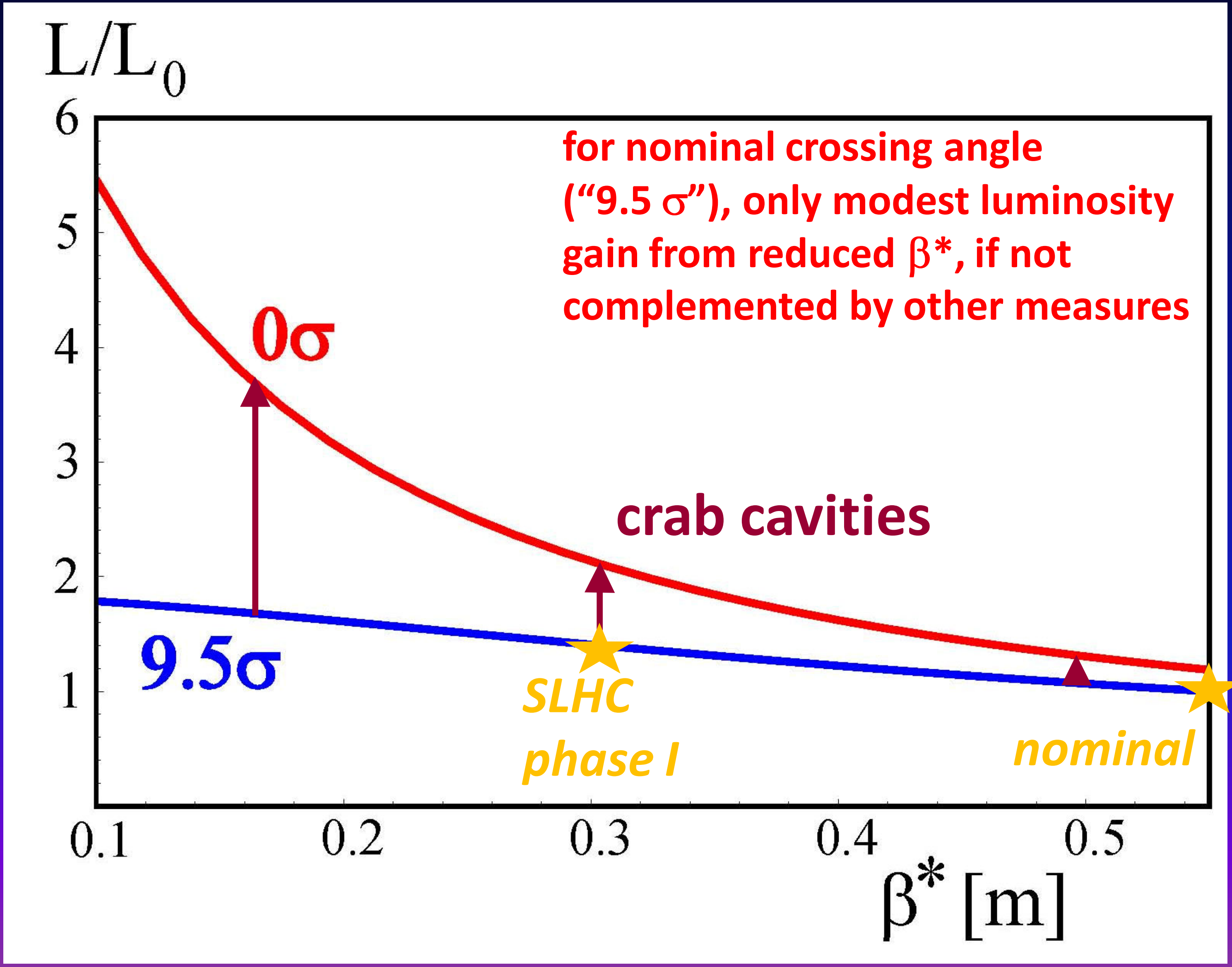




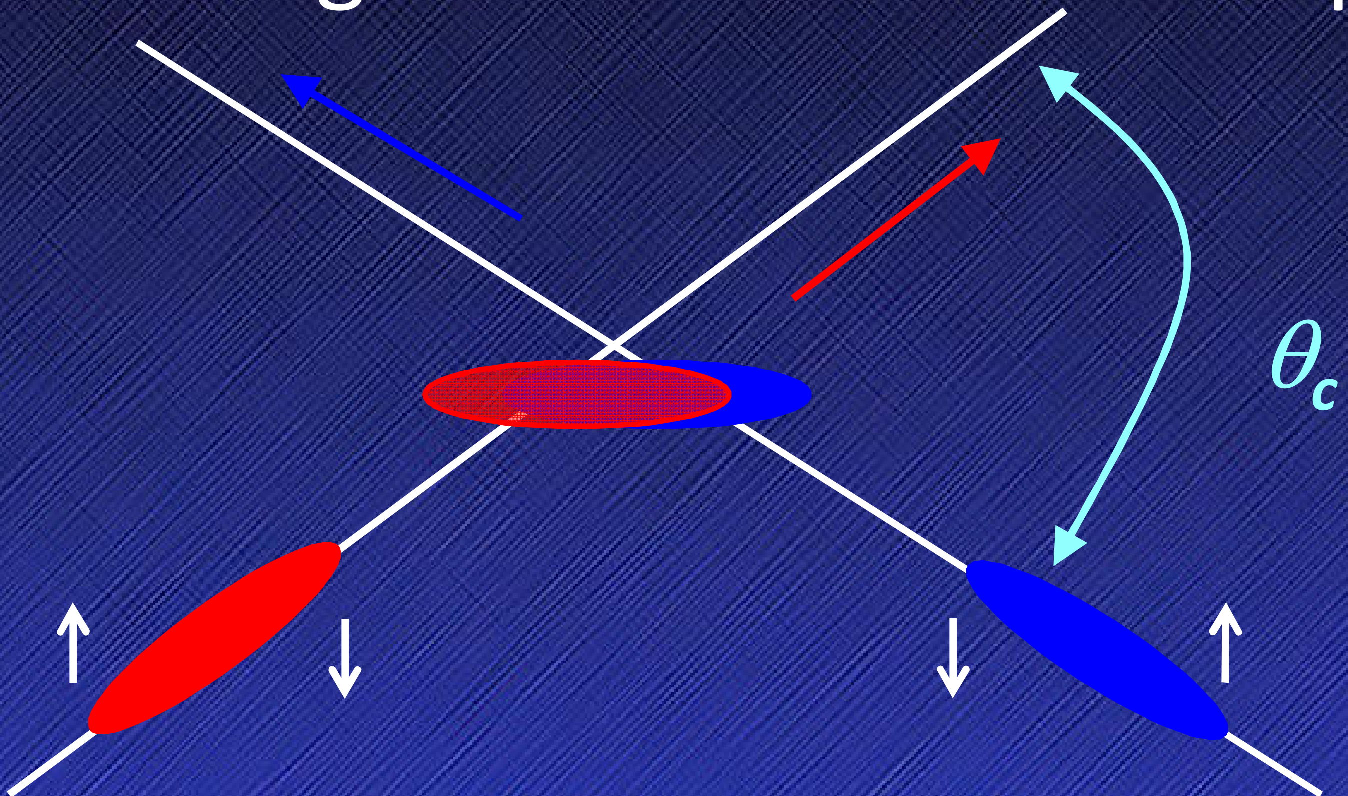
effective beam size $\sigma \rightarrow \sigma / R_\phi$

$\phi \sim 1/\beta^*$!

reducing β* in LHC



crab crossing restores bunch overlap



- RF crab cavity deflects head and tail in opposite direction so that collision is effectively "head on" for luminosity and tune shift
- bunch centroids still cross at an angle (easy separation)
- 1st proposed in 1988, in operation at KEKB since 2007

$\rightarrow$ ***world record luminosity!***

crab-cavity rf vs bunch shortening rf

bunch shortening rf voltage:

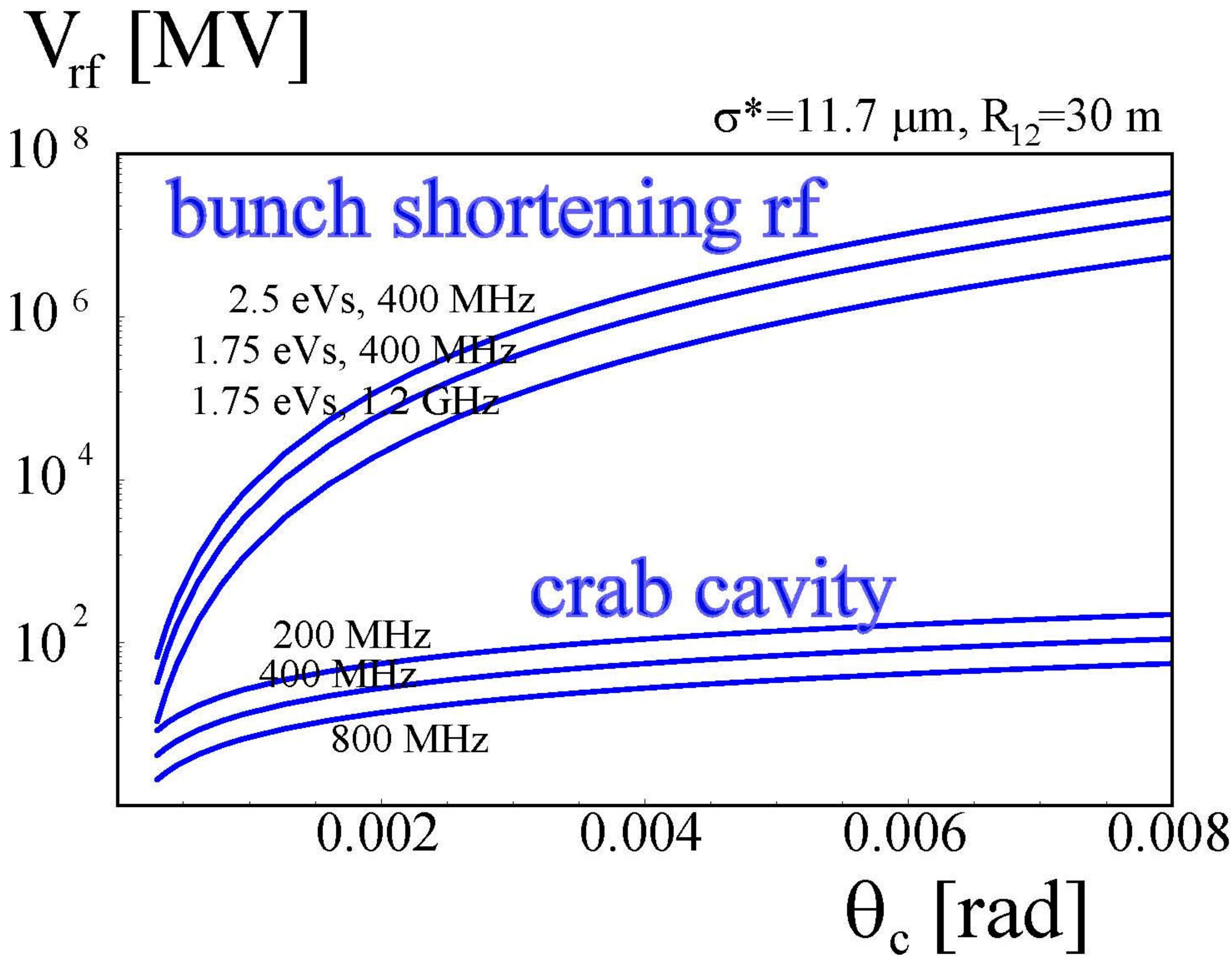
$$V_{rf} \approx \left[\frac{\varepsilon_{\parallel,rms}^2 c^3 C \eta}{E_0 2\pi f_{rf}} \right] \frac{1}{\sigma_z^4} \approx \left[\frac{\varepsilon_{\parallel,rms}^2 c^3 C \eta}{E_0 2\pi f_{rf}} \right] \frac{\theta_c^4}{0.7^4\, 16 \sigma_x^{*4}}$$

unfavorable scaling as 4th power of crossing angle and inverse 4th power of IP beam size, i.e. $\sim 1/\beta^{*4}$; can be decreased by reducing the longitudinal emittance; inversely proportional to rf frequency

crab cavity rf voltage:

$$V_{crab} = \frac{c E_0 \tan(\theta_c / 2)}{e 2\pi f_{rf} R_{12}} \approx \frac{c E_0}{e 4\pi f_{rf} R_{12}} \theta_c$$

proportional to crossing angle & independent of IP beam size, i.e. $\sim 1/\beta^{*1/2}$; scales with $1/R_{12}$; also inversely proportional to rf frequency



F. Zimmermann, U. Dorda, LUMI'05

tune shift & luminosity

$$\Delta Q_{bb} \equiv \frac{N_b}{\gamma\varepsilon}\frac{r_p}{2\pi}\frac{1}{\sqrt{1+\phi^2}}\frac{1}{F_{profile}} \qquad \phi \equiv \frac{\sigma_z \theta_c}{2\sigma^*_{x,y}}$$

Piwinski angle

total beam-beam tune shift at 2 IPs with alternating crossing;

we can increase charge N_b until limit ΔQ_{bb} is reached; to go further we must increase ϕ_{piw}, and/or ε and/or $F_{profile}$ (~$2^{1/2}$ for flat bunches)

$$L = \frac{1}{4\pi} f_{rev} n_b \gamma \frac{1}{\beta^*(\gamma\varepsilon)} N_b^2 \frac{1}{\sqrt{1+\phi^2}}$$

$$= \frac{\pi}{r_p^2} f_{rev} n_b \gamma \frac{(\gamma\varepsilon)}{\beta^*} \Delta Q_{bb}^2 F^2_{profile}\sqrt{1+\phi^2}$$

at the b-b limit, larger Piwinski angle &/or larger emittance increase luminosity!

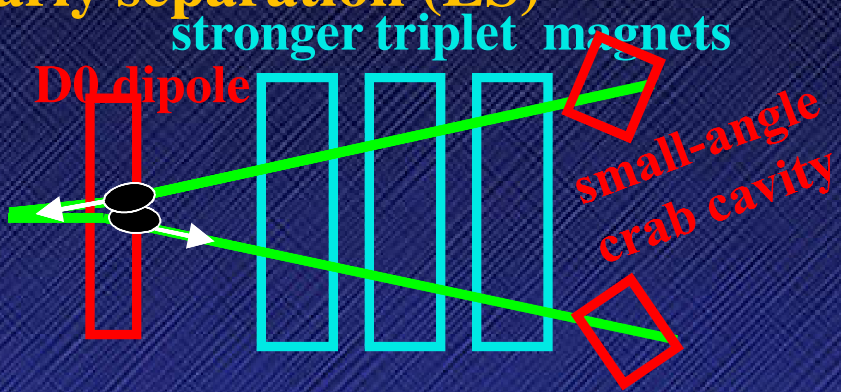
four phase-II upgrade scenarios

1. Early Separation (ES)
2. Full Crab Crossing (FCC)
3. Large Piwinski Angle (LPA)
4. Low Emittance (LE)

four "phase-2" IR layouts

early separation (ES)

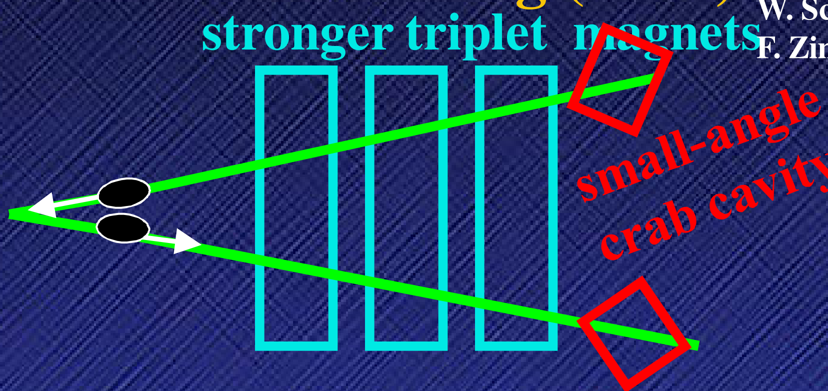
J.-P. Koutchouk



- early-separation dipoles in side detectors , crab cavities
  → hardware inside ATLAS & CMS detectors,
  first hadron crab cavities; off-δ β

full crab crossing (FCC)

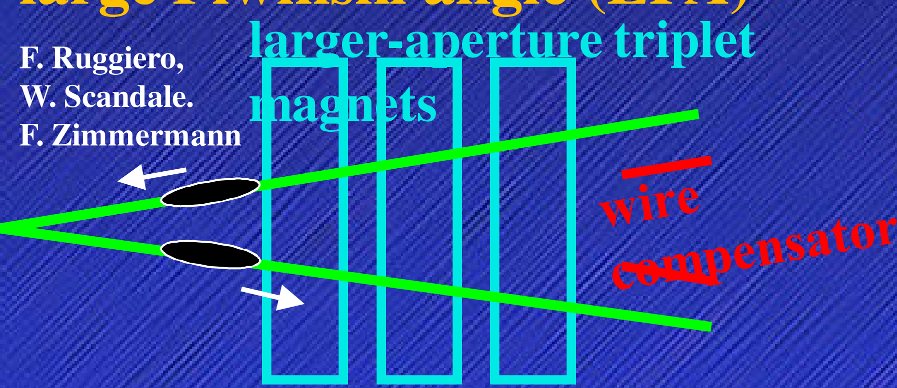
L. Evans,
W. Scandale,
F. Zimmermann



- crab cavities with 60% higher voltage
  → first hadron crab cavities, off-δ β-beat

large Piwinski angle (LPA)

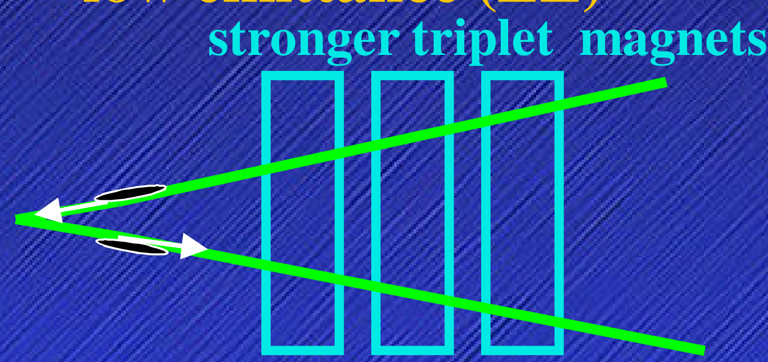
F. Ruggiero,
W. Scandale.
F. Zimmermann



- long-range beam-beam wire compensation
  → novel operating regime for hadron colliders,
  beam generation

low emittance (LE)

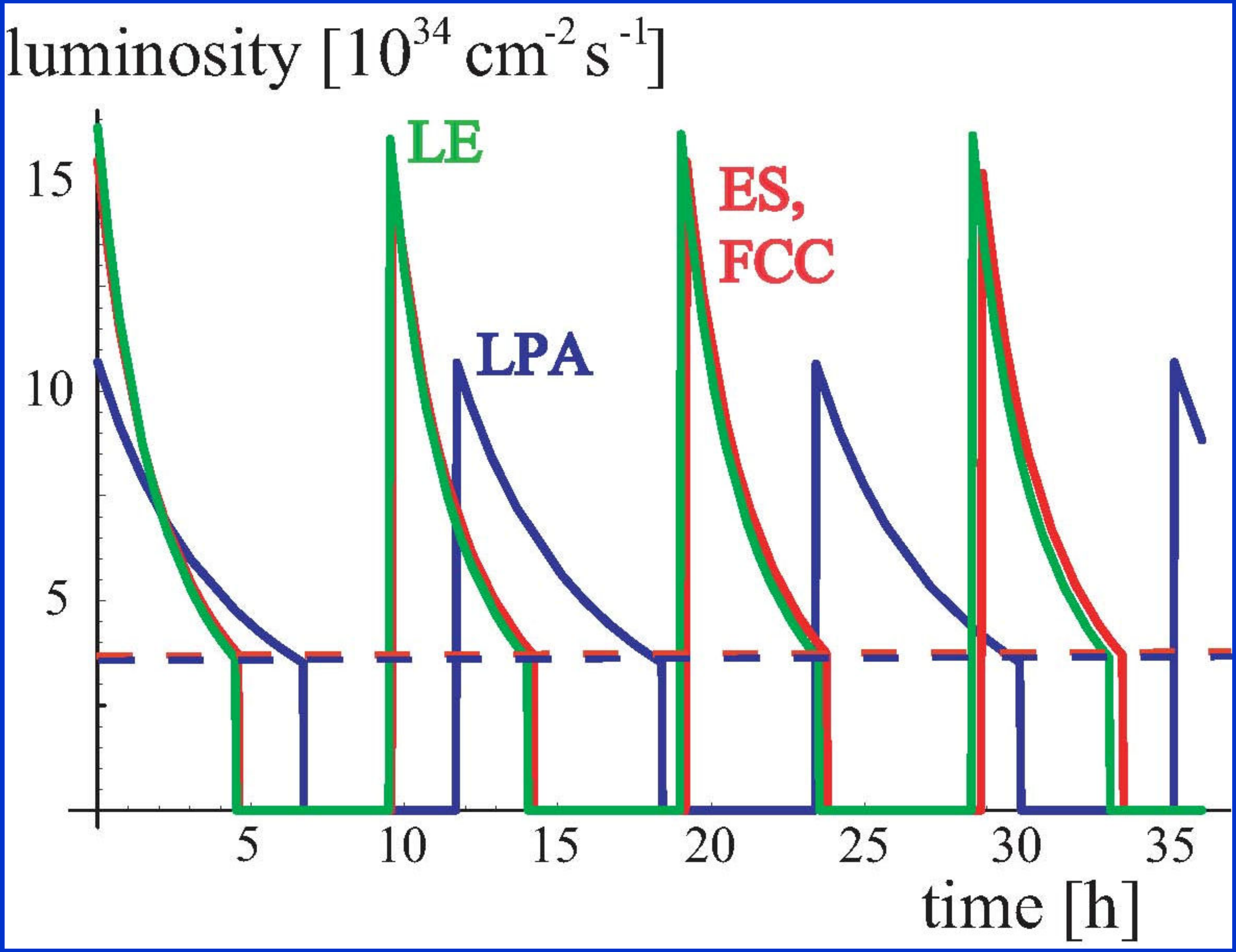
R. Garoby



- smaller transverse emittance
  → constraint on new injectors, off-δ β-beat

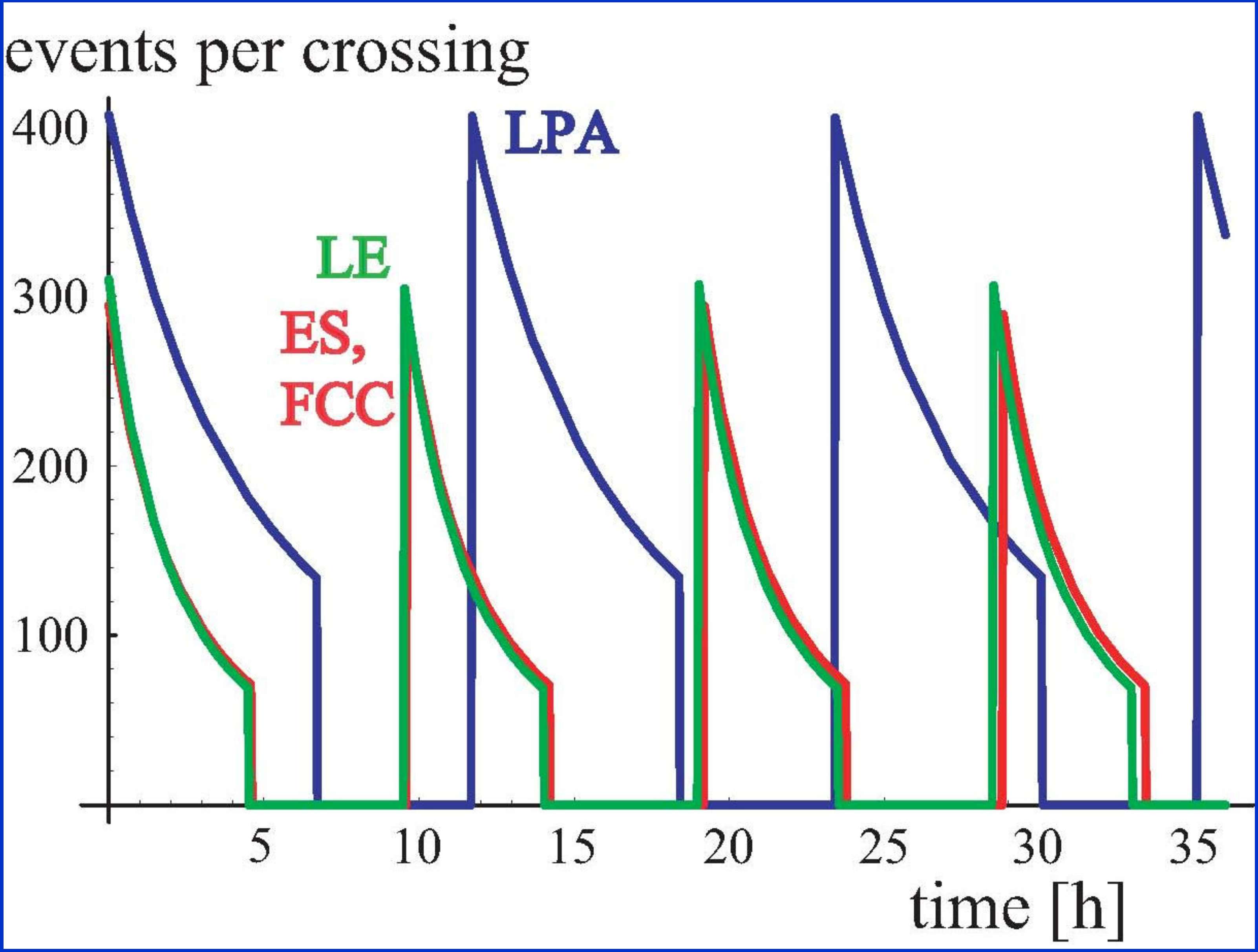
parameter	symbol	nominal	ultimate	ph. I	ES	FCC	LE	LPA
transverse emittance	ε [μm]	3.75	3.75		**3.75**	**3.75**	**1.0**	**3.75**
protons per bunch	N_b [10^{11}]	1.15	1.7		**1.7**	**1.7**	**1.7**	**4.9**
bunch spacing	Δt [ns]	25	25		**25**	**25**	**25**	**50**
beam current	I [A]	0.58	0.86		**0.86**	**0.86**	**0.86**	**1.22**
longitudinal profile		Gauss	Gauss		**Gauss**	**Gauss**	**Gauss**	**Flat**
rms bunch length	σ_z [cm]	7.55	7.55		**7.55**	**7.55**	**7.55**	**11.8**
beta* at IP1&5	$\beta*$ [m]	0.55	0.5	0.3	**0.08**	**0.08**	**0.1**	**0.25**
full crossing angle	θ_c [μrad]	285	315	410	**0**	**0**	**311**	**381**
Piwinski angle	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	0.64	0.75	1.26	**0**	**0**	**3.2**	**2.0**
geometric reduction		0.84	0.80	0.62	**0.77**	**0.77**	**0.30**	**0.48**
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	1	2.3	3.0	**14.0**	**14.0**	**16.3**	**11.9**
peak events per #ing		19	44	57	**266**	**266**	**310**	**452**
initial lumi lifetime	τ_L [h]	22	14	11	**2.2**	**2.2**	**2.0**	**4.0**
effective luminosity ($T_{turnaround}$=10 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	0.46	0.91	1.07	**2.3**	**2.3**	**2.5**	**2.7**
	$T_{run,opt}$ [h]	21.2	17.0	14.9	**6.9**	**6.9**	**6.4**	**9.0**
effective luminosity ($T_{turnaround}$=5 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	0.56	1.15	1.38	**3.4**	**3.4**	**3.7**	**3.7**
	$T_{run,opt}$ [h]	15.0	12.0	10.5	**4.9**	**4.9**	**4.5**	**6.3**
e-c heat SEY=1.4(1.3)	P [W/m]	1.1 (0.4)	1.0 (0.6)		**1.0 (0.6)**	**1.0 (0.6)**	**1.0 (0.6)**	**0.4 (0.1)**
SR heat load 4.6-20 K	P_{SR} [W/m]	0.17	0.25		**0.25**	**0.25**	**0.25**	**0.36**
image current heat	P_{IC} [W/m]	0.15	0.33		**0.33**	**0.33**	**0.33**	**0.78**
gas-s. 100 h τ_b	P_{gas} [W/m]	0.04	0.06		**0.06**	**0.06**	**0.06**	**0.09**
extent luminous region	σ_l [cm]	4.5	4.3	3.3	**5.3**	**5.3**	**1.6**	**4.2**
comment		nominal	ultimate		**D0+CC**	**crab**		**wire com.**

luminosity evolution



average luminosity

event pile up



"luminosity leveling"

very fast decay of luminosity (few hours) dominated by proton burn off in collisions

$$L(t) = \frac{\hat{L}}{\left(1 + t/\tau_{eff}\right)^2}$$

$$\tau_{eff} = \frac{N_b n_b}{n_{IP} \hat{L} \sigma_{tot}}$$

luminosity leveling (changing θ_c, β^* or σ_z in store to keep luminosity constant) $\rightarrow$ **reducing maximum event pile up & peak power deposited in IR magnets**

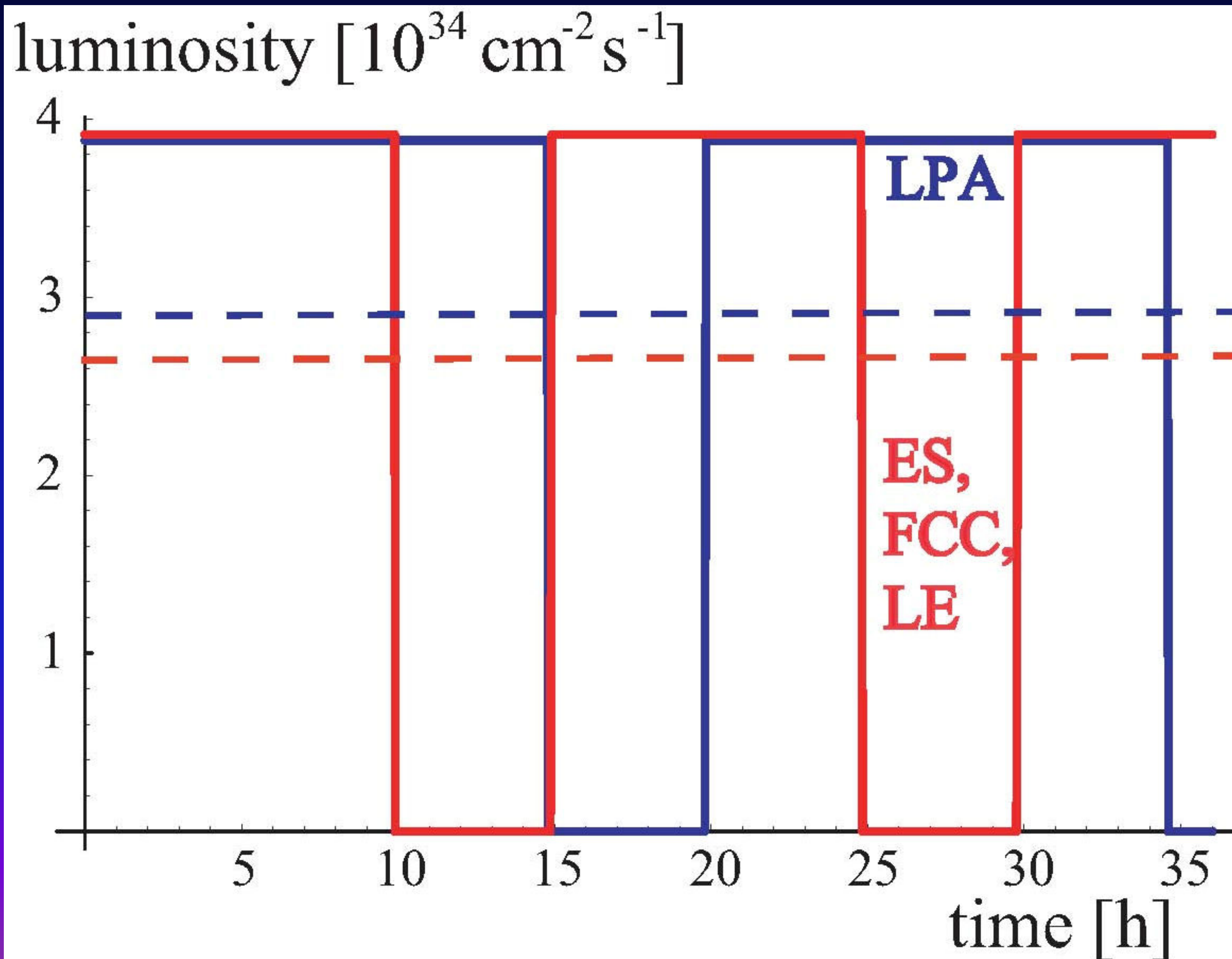
leveling with crossing angle → distinct advantages:

- increased average luminosity if beam current not limited
- operational simplicity

natural option for crab cavities

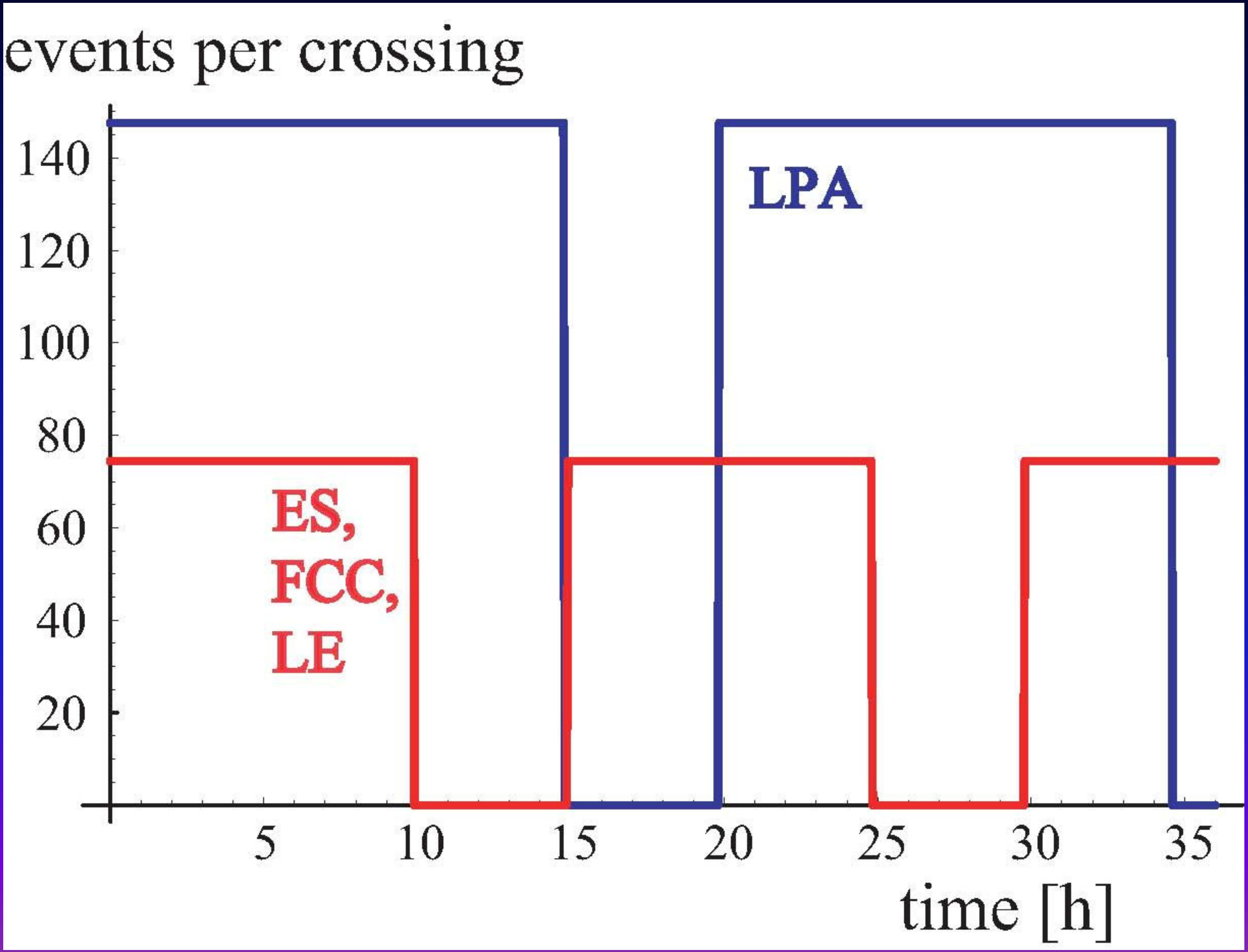
first test in LHC heavy-ion collisions for ALICE?

luminosity with leveling



average
luminosity

event pile up with leveling



experimenters' preference:
(T. Wyatt, LHCC Upgrade Session, 1 July 2008)

- ✓ no accelerator components inside detector
- ✓ lowest possible event pile up
- ✓ possibility of easy luminosity leveling

→ **Full Crab Crossing upgrade**

four(!) LHC crab cavity applications

- ~16% **geometric luminosity** gain for nominal LHC, **~60% gain for SLHC phase I**
- tool for **luminosity leveling** and controlling beam-beam tune shift
- **boosting the beam-beam limit**?! (KEKB example)
- off-momentum cleaning, to relax IR7 constraints, and to **reach β^*~0.15 m**

crossing angle → reduced beam-beam limit?

lepton colliders:

strong-strong beam-beam simulations predicted an **increase in** the KEKB **beam-beam tune shift limit by a factor ~2 for head-on collision compared with the original crossing angle**. This was the primary motivation for KEKB crab cavities [K. Ohmi] Higher luminosity with crab cavity / head-on collision confirmed!

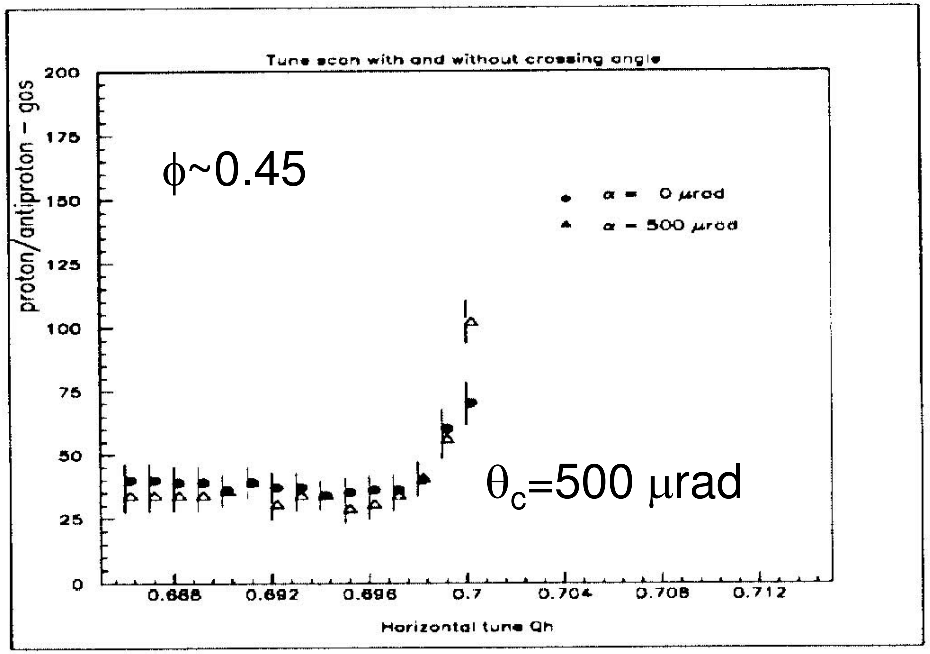
hadron colliders:

RHIC operates with **crossing angles of +/- 0.5 mrad** due to limited BPM resolution and diurnal orbit motion. Performance of proton stores is very irreproducible and frequently occurring **lifetime problems could be related to the crossing angle**, but this is not definitely proven. [W. Fischer]

Tevatron controls crossing angle to **better than 10 μrad**, and for angles of 10-20 μrad **no lifetime degradation** is seen. [V. Shiltsev]

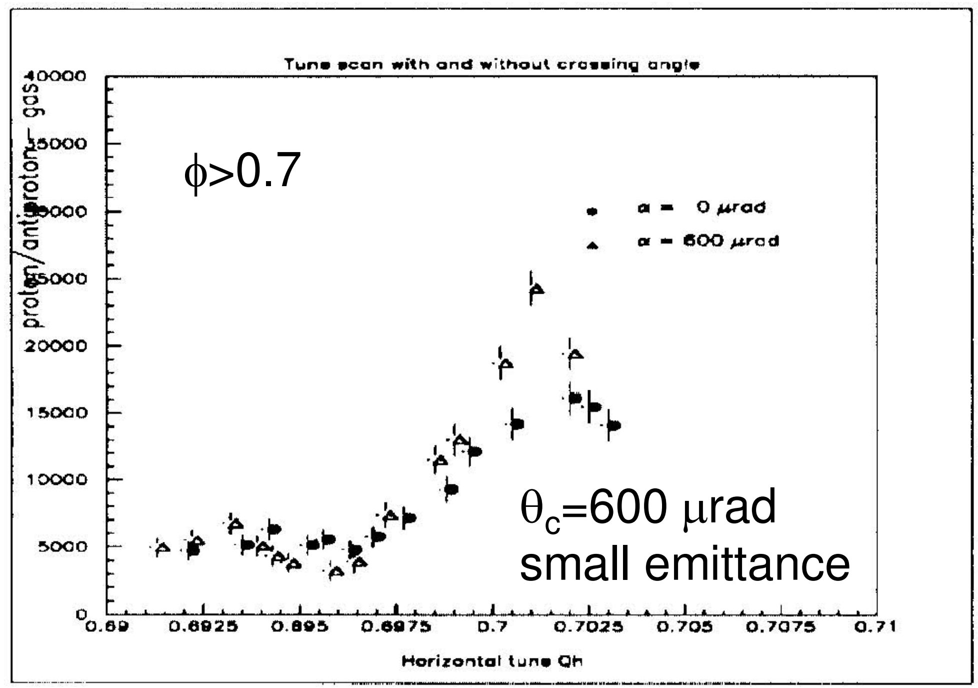
historical experiments at SPS collider

K. Cornelis, W. Herr, M. Meddahi, "Proton Antiproton Collisions at a Finite Crossing Angle in the SPS", PAC91 San Francisco



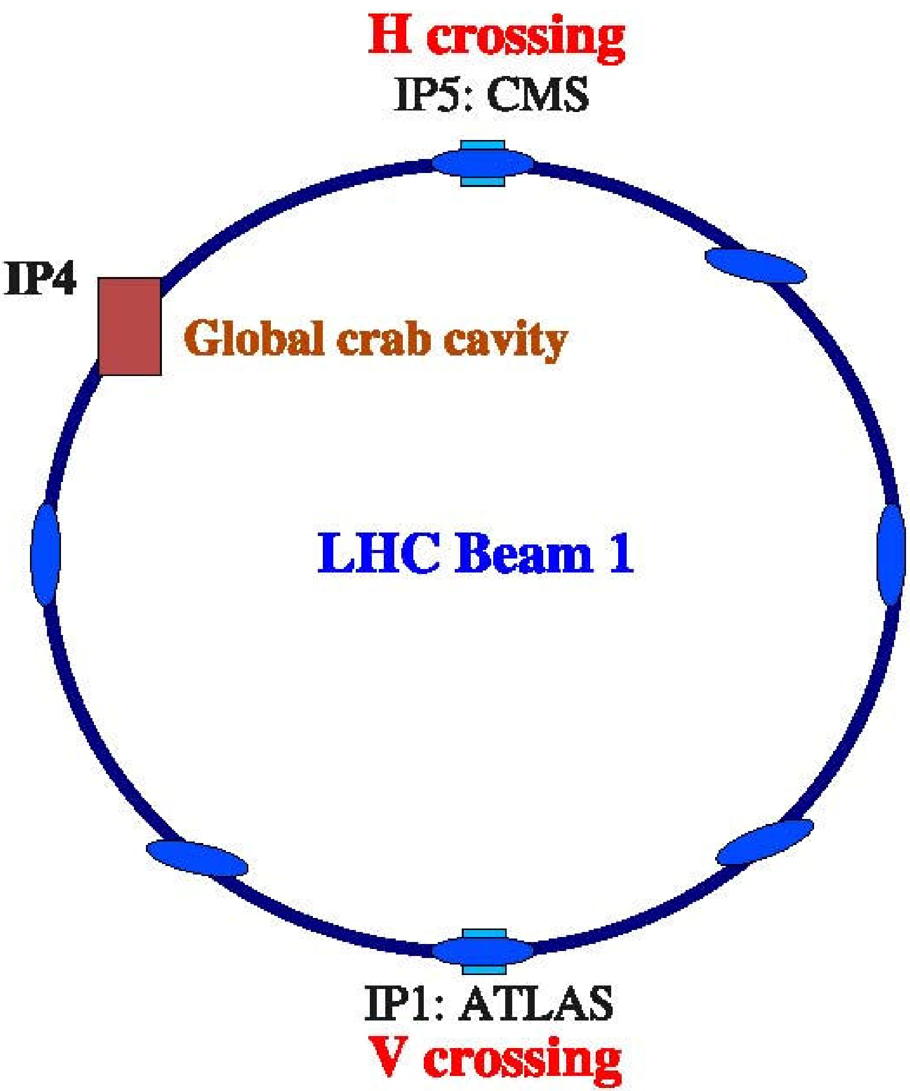
tests up to ϕ>0.7 showed (almost) no additional beam-beam effect

present nominal LHC: ϕ~0.64,
phase-I upgrade: ϕ~1.25!

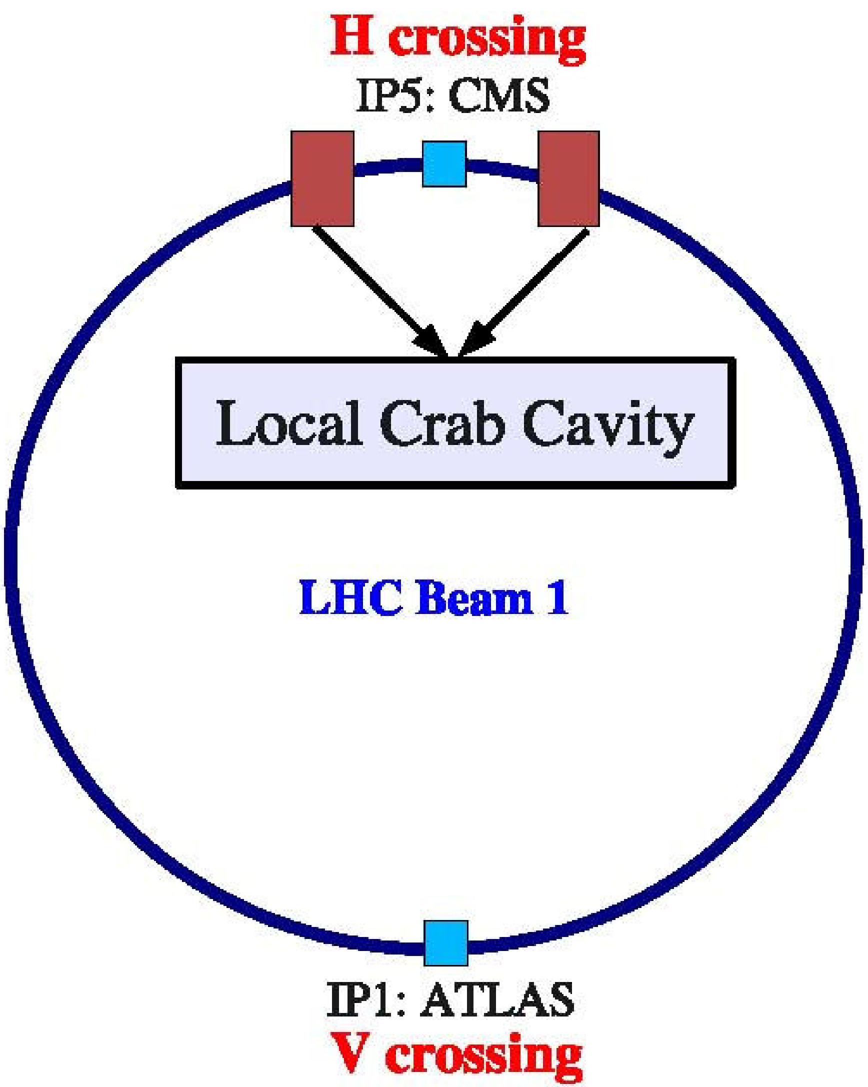


staged implementation

phase I



phase II



baseline crab cavity parameters

one cryomodule/beam

squashed two-cell cavity, 800 MHz (2 K)

nominal voltage 2.5 MV (margin)

nominal transverse size: 23 cm (x0.8)

nominal length ~3 m / cryomodule

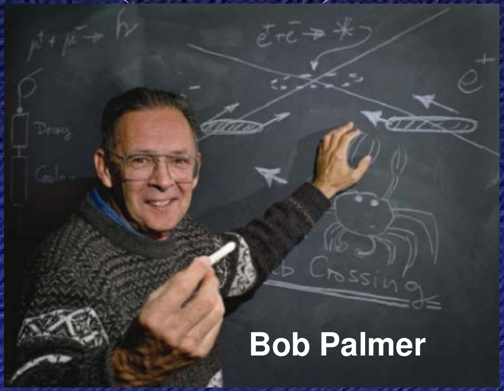
all couplers oriented in vertical plane

Rama Calaga

brief crab-cavity history

1970s : CERN/Karlsruhe s.c. deflecting cavities for Kaon separation (2.86 GHz)

1988: Bob Palmer proposes crab cavities for linear colliders



1989: proposal of crab cavities for e+e- factories
(Katsunobu Oide & Kaoru Yokoya)

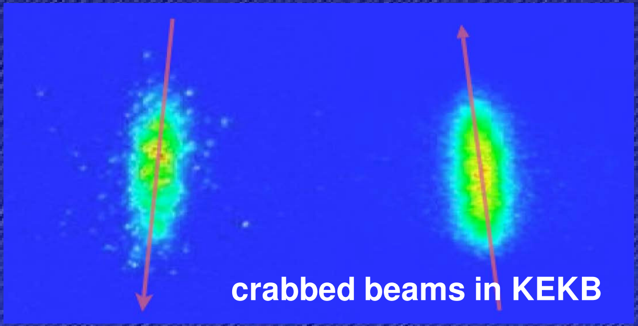
1991: Cornell 1.5 GHz scaled model crab cavity

1993: KEK 500 MHz crab cavity with extreme polarization

2001: crab cavity option in LHC upgrade feasibility study , LHC Project Report 626

2004-2006: LHC crab cavities in CARE-HHH workshops HHH-2004, LUMI-05, LUMI-06

2006/07: launch of US-LARP crab activities



2007: KEKB crab cavity operation

2007: launch of LHC-ILC crab collaboration
& LHC-crab twiki pages

2008: 25-26. February, Joint BNL/US-LARP/CARE-HHH mini-workshop on LHC crab cavities, LHC-CC08

2008: April, ICFA Mini-Workshop on Deflecting/Crabbing Cavities, Shanghai

2008: July, launch of joint CERN-KEK crab cavity video meetings

2008: 20. August, LHC Crab-Cavity Validation Mini-Workshop

2009: 16-18 September, LHC-CC09

from KEKB to LHC

	LHC nominal	SLHC phase- I	SLHC phase-II "FCC"	KEKB
σ_z [mm]	75.5	75.5	75.5	7.0
σ_x^* [μm]	16.6	12.2	6.3	103
θ_c [mrad]	0.285	0.410	0.673	22.0
ϕ	0.64	1.26 (w/o crab)	4.1 (w/o crab)	0.75 (w/o crab)

LHC-CC09

3rd LHC Crab Cavity Workshop, jointly organized by CERN, EuCARD-ACCNET, US-LARP, KEK, & Daresbury Lab/Cockcroft Institute

workshop charges:

1. down-select crab-cavity design & advance cryomodule design
2. review beam simulation results and operational procedures for prototype tests
3. establish strategy for full crab crossing scheme for LHC phase-II upgrade

LHC-CC 09 workshop structure

Wednesday
Setting the scene
Layout, dynamics & potential
Cavity design
Cryomodule design

Thursday
Crab cavity integration
Cryomodule construction
Phase I, validation
Phase II, strategy

Friday
Planning & milestones
Down selection
Advisory board – closed session
Public close out

statistics & organization

- ~50 pre-registered participants

  25 CERN, 3 KEK, 5 CI/DL, 3 BNL, 2 SLAC,
  2 FNAL, 1 Cornell, 1 JLAB, 1 INFN, 1 DESY,…
- 11+1 sessions, each ending with 30-60 minutes discussion
- Advisory Board closed session & public close-out on Friday
- no-host dinner on Thursday in Saint Genis

Restaurant Le Coq Rouge

LHC Crab Cavity Advisory Board

1. Ilan Ben-Zvi, BNL
2. Swapan Chattopadhyay, CI → Mike Poole, CI
3. Georg Hoffstaetter, Cornell
4. Erk Jensen, CERN
5. Philippe Lebrun, CERN
6. Steve Myers, CERN (**Chair**)
7. Marzio Nessi, CERN
8. Eric Prebys, LARP
9. Tor Raubenheimer, SLAC
10. Emmanuel Tsesmelis, CERN
11. Jim Virdee, CERN
12. Akira Yamamoto, KEK

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13. Walter Scandale (CERN)
14. Andrei Seryi (SLAC)
15. Stefan Simrock (DESY)
16. Laurent Tavian (CERN)
17. Alessandro Variola (CNRS-IN2P3)

Thank You!

LHC-CC09 LOC

Rama Calaga
Jean-Pierre Koutchouk
Delphine Rivoiron (secretariat)
Rogelio Tomas
Joachim Tückmantel
Frank Zimmermann

conclusions

nominal LHC is challenging

crab cavities can help us, in more than one way, to increase the luminosity & to improve conditions for the LHC experiments

crab cavity success at KEKB supports the case

2-stage implementation for LHC looks natural

LHC-CC09 will scrutinize the plan(s)

enjoy the workshop & happy crabbing!